Mechanical polishing of fan blade by a prototype random-orbital tool

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The contributions of the authors are as follows:

- I provided the initial project direction, development of the experimental methodology, collection and compiling of data, and manuscript preparation.
- Assoc/Prof Yeo Swee Hock provided the outline of manuscript, review, analyses and editing of manuscript.

- I designed the tooling at Pratt & Whitney and performed all the laboratory work at the Advanced Remanufacturing and Technology Centre (ARTC). I also analyzed the data. All microscopy, including sample preparation, was conducted by me in the Metrology Laboratory at ARTC.

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Edgar Jeevan Danaraj

**NANYANG
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SINGAPORE

MECHANICAL POLISHING OF FAN BLADE BY A PROTOTYPE RANDOM-ORBITAL TOOL

EDGAR JEEVAN DANARAJ

School of Mechanical and Aerospace Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
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2021

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List of Symbols

Ra	Arithmetical mean deviation of the assessed profile
Rz	Maximum peak to valley height of the profile
Rku	Kurtosis of the assessed profile
Rsk	Skewness of the assessed profile.
Sa	Arithmetical mean height of the surface
Sz	Maximum height of the surface
Sku	Kurtosis of height distribution
Ssk	Skewness of height distribution
PSD	Power Spectral Density
FFT	Fast Fourier Transform
MQL	Minimum Quantity Lubrication
Mohs	A scale of hardness for minerals
pH	Acidity or alkalinity of a solution on a logarithmic scale
HV	Vickers Pyramid Number
FEPA	Federation of European Producers of Abrasives
CCI	Coherence Correlation Interferometry
FOV	Field of View
dBc	Decibels relative to the carrier
FLIR	Forward-looking infrared
V_c	Cutting Speed
MRR	Material Removal Rate
ρ_w	density of the abrasive disk
N	number of the active particles
C_o	removal rate caused by chemical corrosion
ω	angular velocity of the abrasive disk
V	Linear velocity of the abrasive disk

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Abstract

The main objective of this study is to better understand the influence of water and air coolant-induced surface texturing and its characterization by a new random-orbital polishing method and prototype tool. Mechanical polishing is the most common process to remove surface irregularities on fan blades such as scallop height features, while maintaining the required dimensional limits and textures. After the polishing process, the part will undergo shot peening, vibratory finishing and later, painting and coating at the final stages. It is therefore essential for the fan blade surface to pre-treated with appropriate surface conditions to promote good surface-to-surface adhesion at the end of the manufacturing cycle. The existing method uses a single-axis rotary polishing tool where an external water coolant source is performed ad-hoc. This polishing method can produce average surface roughness, Ra , of $1.0\text{ }\mu\text{m}$ that satisfies the requirement. However, this form is aggressive and has a high material removal rate, resulting in excessive reduction in material thickness, thus warrants rejection of costly fan blade. The criteria require surface roughness, Ra , between 0.8 to $1.0\text{ }\mu\text{m}$ and maximum height profile Rz , between 5.0 to $6.0\text{ }\mu\text{m}$ for post-polishing condition, while maintaining low material removal rate to prevent under-thickness of the fan blade. Experimental trials were performed on fan blade specimens at the leading-edge sections and its surface topography characterized by coherence correlation interferometry. A range of different abrasive grit sizes was tested for suitability of media selection. Integrating in-line cooled air with deionized water to the process achieved desirable surface roughness, Ra , of $0.8\text{ }\mu\text{m}$ and height profile Rz , of $5.8\text{ }\mu\text{m}$, while simultaneously removing all traces of scallop height features and maintaining the leading-edge thickness within tolerance. Taking into consideration that the surface texture measurements are random in nature, the corresponding polishing methods were also analyzed with statistical functions by fast Fourier transform (FFT) and power spectral density (PSD). Comparison between the surface texture parameters or statistical functions with the corresponding polishing methods, were then established. The surface integrity of the polished fan blade and wear condition of the abrasive disk are also reported in this study.

1. Introduction

1.1 Background

Mechanical polishing is widely practiced in the aerospace industry for engine airfoil components such as fan blades, turbine blades and stator vanes. Airfoil components are designed to have thin, lightweight and complex geometries with smooth surfaces that ensure an ideal flow of air in the gas path. These geometries are contoured and require a high level of dimensional precision and surface finish. Any machining defect on the concave and convex profiles will require polishing to a smooth and uniform texture. After the polishing process, the part will undergo shot peening, vibratory finishing and later, painting and coating at the final stages. It is therefore essential for the fan blade surface to reach a certain roughness value in order to promote good surface-to-surface adhesion at the end of the manufacturing cycle.

1.2 Motivation

Random-orbital polishing is predominantly used in the automotive sector but not widely explored for the aerospace industry. Firstly, this type of polishing mechanism induces vibration motion instead of conventional rotary motion for a less aggressive material removal action. Secondly, the conventional method by rotary polishing mandates the use of a specific type of abrasive media and grit size. Studying a range of abrasive grit sizes for random-orbital polishing will be beneficial in understanding trends in the post-finished results. This is to support random-orbital polishing as an alternate method in the manufacturing process.

From the tool design perspective, typical polishing employs the use of belts or circular disks without any holes to allow through-coolant capability. With slight modification done to the tooling and consumables, in-line air and liquid can improve the process by cooling the part more effectively. The abrasive bond is made of an organic chemical compound called formaldehyde and this poses a significant danger to human health due to its toxicity and volatility. A liquid coolant such as deionized water, may reduce the dust generation and emission of formaldehyde, thereby lowering the combustible dust explosion risk and also promote human safety.

1.3 Problem statement

Poor machining of fan blades may generate irregularities on surface which require sufficient material removal to eliminate the deviation and maintain geometrical or dimensional limits simultaneously. The most common defects in machining are scallop height features, due to abnormal tool or fixture vibration.

Surface peaks are sharp and considered as stress concentration where cracks may be initiated and subsequently propagate, causing fatigue failure, this is non-compliance of airworthiness standards for fan blade components in aero engines. Therefore, surface defects must be removed, typically by mechanical polishing while attaining the required surface finish and thickness dimension.

The existing production method of polishing fan blade deploys the use of a single-axis rotary tool with one type of abrasive grit size. The fan blade surface is wetted by external application of deionized water and wiped at intervals to keep it clean, thereby disrupting the process. The heat generated in the existing polishing process is relatively high and will induce thermal damage or deformation to the aluminum alloy fan blade.

Moreover, the abrasive disk also needs to be checked frequently for wear and replacement. With better heat dissipation by introducing air and deionized water dynamically, the process could improve in terms of tool performance and finishing quality.

The rotary polishing tool has a single-axis rotational movement where the abrasive pad spins primarily around its axis at high speeds, creating an aggressive cutting action. The challenge of this motion is the generation of lay in the surface texture which is detrimental to the functionality of the fan blade.

The other issue is high rate of material removal associated with rotary polishing which would result in edge thinning or under-thickness of the fan blade. Thus, it is necessary to test a newly develop a random-orbit tool that is capable of removing surface defects while effectively keeping the part cool, and in continuous motion.

1.4 Research objectives

The main goal is to understand the method in which these mechanisms interact with the random-orbital polishing technique and the implication of the fan blade surface topography. In addition, using deionized water may have a chemical-mechanical reaction with the abrasive to form a slurry, which could influence the surface topography, material removal, micro-hardness and microstructure of the specimen. This will be studied in correlation with the abrasive disk life.

This research presents the feasibility of using random-orbital polishing with an in-line cooling system for surface texturing of defective aero-engine fan blade in terms of improving quality and cost. The aim of this study is to analyze the effects of cold air, and water on random-orbital polished surfaces, including the impact on the abrasive disk life.

A range of abrasive grit sizes for random-orbital polishing will be used for feasibility and correlation between the existing and proposed method. Microstructure and micro-hardness evaluation will be used to verify changes in the specimen. This provides the information to understand the influence of various conditions and their effect on the abrasive disk life.

Roughness measurement is used for surface topography characterization in pre- and post-condition. The fast Fourier transform (FFT) and power spectral density (PSD) functions are also used to evaluate the effects between the rotary and random-orbital polished surfaces. This provides the statistical information to understand the differences or relationship between the various methods. In addition, it is essential that the material removal rate is kept low to prevent an under-thickness condition. Thus, the thickness dimensions of the specimens will be measured in the process.

This research aims to:

1. Develop a prototype random-orbital tool with in-line water and air capability.
2. Study the effects of various polishing conditions on the surface topography, microstructure and material removal on the fan blade.

3. Test a range of grit size and determine the wear characteristics of the abrasive disk.
4. Achieve a specific surface topography according to industry's technical requirement:
 - (i) R_a , between 0.8 to 1.0 μm ;
 - (ii) R_z , between 5.0 to 6.0 μm ;
 - (iii) S_a between 1.0 to 1.8 μm ;
 - (iv) S_z between 9.0 to 15.0 μm .

1.5 Scope of work

The scope of the research is to test the feasibility and proof-of-concept for a new prototyped random-orbital tool. Four different conditions for random-orbital polishing is setup for the trials. Five abrasive grit sizes for each condition are selected for a more complete experimentation.

The experimental conditions for the random-orbital polishing trials are as follows:

- Condition 1. Dry, ambient
- Condition 2. Wet, ambient (deionized water)
- Condition 3. Dry, cold air
- Condition 4. Wet, cold air (deionized water)

2. Literature review

2.1 Polishing methods

Abrasive disk motion is the determining factor for effective polishing by generating the required surface roughness. Axinte et al. [1] used belt polishing for final finishing of components to improve dimensional precision and surface quality. Xiao et al. [2] developed a similar abrasive belt polishing method for blades to achieve the desired surface properties. A proposed polishing method by random-orbital motion is proposed for the fan blade polishing.

Random-orbital disk moves in two directions as opposed to one direction. This tool uses a mechanism that causes the disk to simultaneously rotate in a circle and oscillate in an eccentric pattern inside the circle to generate the vibration amplitude. Therefore, the mechanical action of the abrasive by random orbit is vibratory motion instead of fixed rotation. Mechanical polishing may be performed either in dry or wet condition, and with or without air-cooling. Surface topography of the roughness value is usually based on the Ra parameter and may be influenced by different conditions. Wu D. et al. [3] used flexible abrasive cloth wheel to polish titanium alloy blades in dry condition. The results showed that unevenness, and other defects of the blade surface are effectively removed and the dry method effectively improved the surface quality without exceeding the dimensional limits of the workpiece. The surface roughness is reduced from Ra of 1.2 μm to less than 0.40 μm .

Surface roughness is influenced by the properties of friction of fixed abrasives lubricated by water. When deionized water is applied to the abrasive material, slurry is formed, corresponding to the abrasive mechanism in chemical mechanical polishing. The relative movement of the slurry drawn between the polished surface and the pad creates the material removal process [4].

In some studies, the effect of dry and wet polishing showed that polishing without water increased the surface roughness of the samples because the abrasive grains detached from the polishing tool may embed into the workpiece surface [5]. Wong et al. [6] investigated

the effect of surface roughness on frictional characteristics in deionized water. It is discovered that the friction coefficient and surface roughness decreased with sliding distance in the materials tested with deionized water.

The effects of impinging air jets by compressed cold air have been studied by Choi [7]. It was reported that the effectiveness of the cold air in reducing thermal defects was almost similar to that with liquid coolant with negligible material loss. The formation of tensile stresses in the surface was more evident and surface roughness would rise as the depth of cut increases. It was found that the lack of liquid coolant in using dry cold air was almost certainly the main reason for this phenomenon to occur.

The application of cold air showed some improvements compared with dry polishing. However, many important issues of surface characterization have not been closely examined [8]. Saberi et al. [9] used a grinding technique called minimum quantity lubrication (MQL) technique by compressed cold air jet from a cold air gun (vortex tube principle). This technique involved spraying a mixture of air and oil mist onto the cutting zone directly. MQL improved cooling and lubrication performance through the use of a cold air gun which generated conditioned air at lower temperatures than ambient. The study of cooling effect with minimum quantity lubrication with air jet of 0.4 MPa pressure and 14°C temperature concluded that surface quality improved when compared to dry condition. As such, a condition has been set aside in this study to deploy the MQL technique and verify its combined effect (water and air).

Use of pure air is another alternative but it has relatively poor cooling ability which may lead to low specific heat and low heat conductivity. Due to low mass flow rate of air streams (measured at 1.0 m/s) exiting the holes in the abrasive disk, the heat transfer coefficient will be smaller, regardless of its low temperature.

Design configuration of the abrasive end effector vary from circular wheels or belt types to cylindrical or conical grinding heads. For the circular type of wheels (round-shaped disk), a foam or inflatable backing pad may be used for flexibility on the free form geometry [10]. Axinte et al. [11] demonstrated that combining dual finishing methods

(belt and bob) as a hybrid process would be beneficial for components with complex geometries, removing both machining marks and achieving the required surface roughness to some extent. Zhao et al. [12] optimized the key process parameters for polishing of aero-engine blades to reduce the surface roughness and improve quality of the finish.

2.2 Abrasive types and properties

There are a number of different types of aluminum oxide abrasive. These abrasives are classified by their crystal structure, hardness, grit size and bond coat. The most commonly used for polishing are either calcined or polycrystalline alumina. The harder crystal structure is corundum or alpha alumina (mohs 9) [13]. The Vickers hardness is approximately 2,000 HV. This property makes it suitable for mechanical polishing. Typically, aluminum oxide abrasive becomes acidic, of pH 4.5, when in contact with water.

Aluminum oxide abrasive selected for the experimental trials comprises of cryolite and alpha alumina, which is high in purity and dispersion. Fused cryolite is used as a mineral filler for the bond of the agglomerated alumina abrasive grains. This is a well-known fact of cryolite being used as a polishing aid to enhance cutting performance. The manufacture of such particle sizes is controlled under tight limits with specific focus on grain control with uniform particle size distribution. The particles are blocky in shape and durable. Characteristics for some grits are as fine as 3 μm with 99.65% aluminum oxide typical purity levels.

Figure 1(a) shows a random-orbital abrasive disk with several holes for through-flow capability. A special feature of the selected abrasive was the unique coating bond over an agglomerated grain structure. This was intended to facilitate slurry formulation under wet conditions where the smaller grains would easily breakdown into finer particles and mix with the deionized water.

Figure 1(b) shows the typical grain size ranging between 45 to 48 μm . It can be clearly seen that some areas have relatively wide dispersion. Dispersion is the spacing between

grit particles that coat the substrate. The dispersion is a dendrite-like structure and is more noticeable in the coarser grits where an open coat results in visible exposure of the substrate. As such, it is important for a variety of coarse and fine grit sizes to be experimented with different conditions. A more open dispersion allows more particles to evacuate and avoid clogging. At the same time, the abrasive may penetrate deeper into the specimen surface leaving scratch marks.

Figure 1(c) shows a 3D profile of the agglomerated grain structure plateaus at 713.9 μm in height and 945 μm in width. Figure 1(d) shows recessed valleys spread across the abrasive disk surface and these regions could have ability to contain a substantial volume of water within the structure. As the agglomerated grains wear down, the valley depths will become shallower, thus having less holding capacity.

Figure 1. (a) Customized hole pattern in the bonded abrasive disk mated to the backing foam pad, (b) 2D section of an agglomerated abrasive structure of P320 grit size, (c) 3D cross-section of a P320 grit size and (d) surface area size of agglomerated abrasive structure of P320 grit size and arrows indicating recessed valleys.

For the agglomerated configuration shown in figure 2, each granulate is a fixed cluster in which numerous abrasive grains are bound to each other by a resin, acting as a bonding bridge. The unique bond allows granulates consisting of many abrasive grains bonded together at different layers in height. As the agglomerated abrasive grains wears out during operation, mechanical forces expose new grain edges for effective cutting action. This produces a consistent surface profile throughout the regenerative wear cycle of the structure.

Figure 2. Agglomerated bonded abrasive structure.

In this configuration, the abrasive will work to produce a uniform stock removal rate as the structured layer wear out exposing the underlying new grains. Compared to the single configuration agglomerated abrasives have been proven to produce significantly more uniform finish combined with fewer setups of different grades. The abrasive cluster in the resin coat appears rougher as compared to conventional abrasives.

Backing materials are part of the abrasive disk layer that are used as platforms to hold and support the abrasive grains. The range of flexibility of the materials is characterized by stiffness rating, from stiffest to most flexible. Flexural characteristics ensures that the bonding coat remain intact when stretched thus controlling crack formation in the abrasive coat. The backing material used for the experimental trials is cloth type and single flex structure. The backing disk is mounted on the polishing pad, which is made of soft-density foam material.

2.3 Surface texturing

It has always been the misconception for airfoil surfaces to have a smooth surface hence “the lower roughness value the better”. However, this perception is not always true. For instance, in a hollow fan blade that requires an additional skin layer to be joined to the body, adhesive resin material may be added to the bonding process at a later stage in the manufacturing cycle. Along with several other thermal coating and erosion coating for heat and wear resistance, the surface of the main body may require a unique texture or roughness value in order to meet a specific bond strength capability.

Special surface treatment processes like etching or anodizing will ensure the adequate preparation of the material for bonding. Other abrasive processes such as blasting or media finishing is used in other scenarios where the surface needs roughening for improved adhesion such as painting or primer coating. Considering this application, it would therefore be beneficial for the surface to have a matte or satin finish designation instead of mirror or lustrous finish. Therefore, the required surface finish may be biased towards having a satin or matte finish with tribological requirement for the surface to hold the coating effectively.

Surface roughness is defined as the irregularities in the material surface texture that are inherent in the abrasive manufacturing process excluding waviness and form errors. It is quantified by the vertical deviations of a real surface from its ideal form. The greater the deviations the rougher the surface will appear to be. Roughness is regarded as a high-frequency short-wavelength component of a measured surface.

For measurement the amplitude and frequency are evaluated to ensure that a surface is fit for purpose. An example where surface texture is closely linked to function is described in the case of two moving surfaces in close proximity. The surface textures of the two parts in contact with one another will affect wear or sealing qualities.

Surface roughening enhances the adhesion of a coating to the substrate due to the larger surface area and the anchoring effect of the micro-porous structure of the roughened surface profile. When bonding two dry surfaces without epoxy, Ra or Sa is the more

important parameter. The goal in these applications is to create interlocking “teeth” to forge a tighter grip. The higher the Ra or Sa , or the bigger the teeth, the better the interlocking capabilities.

The Sa parameter (eq 1) is the arithmetic mean of the absolute value of the height within a sampling area. Sz parameter (eq 2) is the maximum height of the areal surface (peak-to-valley height). Sku is the kurtosis of the areal surface (topography height distribution). The Sku parameter (eq 3) is a measure of the sharpness of the surface height distribution and gives and indicates of ‘spikiness’ of the surface.

Sku indicates the presence of inordinately high peaks or deep valleys ($Sku > 3.00$) or lack of thereof ($Sku < 3.00$) making up the surface. 3D surfaces with random amplitude distribution will have zero skew. Dominant peaks will have a positive skew, while dominant valleys will have a negative skew. Ssk parameter (eq 4) is the skewness of the surface and gives indication of load carrying capacity.

$$Sa = \frac{1}{A} \int \int_A |Z(x, y)| dx dy \quad \text{Eq 1}$$

$$Sz = Sp + Sv \quad \text{Eq 2}$$

$$Sku = \frac{1}{Sq^4} \left[\frac{1}{A} \int \int_A (Z(x, y))^4 dx dy \right] \quad \text{Eq 3}$$

$$Ssk = \frac{1}{Sq^3} \left[\frac{1}{A} \int \int_A (Z^3(x, y)) dx dy \right] \quad \text{Eq 4}$$

2.4 Polishing mechanism

A full understanding of the polishing mechanism in how surface irregularities are smoothed by abrasive particles is still unresolved. With regards to abrasion and surface flow mechanisms, polishing is regarded as an abrasive or grinding process at a very fine range where surface irregularities are removed by cutting action of the abrasives [14]. Another suggestion by Desch [15] is that surface smoothing happens by surface flow and material redistribution; the material from surface peaks ‘flows’ to fill up the valleys and produces a thin vitreous film on the surface, often referred to as the “Beilby layer”. In view of the work by Bowden [16], high temperatures play an important part in polishing, where the formation of this layer of film enables sliding to occur.

Two-body and three-body abrasion are defined in order to understand the differences of polishing conditions associated with these mechanisms. Two-body abrasion involves the removal of material by abrasive particles which are held fixed while being moved across a surface, forming a groove. Three-body abrasion involves loose particles which may roll as they contact the wearing surface [17]. The inputs are the two surfaces and a third body which comprises any solid materials, entirely separate from the first two bodies which might be present at the interface between the first and second bodies [18]. The transition from two-body to three-body could be obtained with a ratio of load to slurry concentration depending on the type of abrasive used.

Figure 3. Theoretical illustration of abrasive grain fragmentation during random-orbital motion, and slurry formation by the mechanical reaction with the deionized water.

Abrasive wear can be defined as wear in which hard asperities on one body moving across a softer body under load. These asperities penetrate and remove material from the surface of the softer body leaving grooves in the surface. A common indication for this type of wear is grooving wear [19].

In certain applications requiring super finishing quality, nanofluid is used as a carrier to enhance the heat transfer abilities as compared with the carrier liquid alone [20]. According to research evidence the heat transfer with the mass fraction 0.01% alumina–

water nanofluids is better than that of the mass fraction of 0.005%, 0.05% and 0.10% alumina–water nanofluids as well as deionized water under high heat flux and different flow velocities.

Polycrystalline alumina slurries provide optimal cutting performance in a variety of polishing applications. Under stress, the nanostructured particles allow micro-fracturing, continually exposing new cutting edges that keep the particle sharper than conventional abrasives for higher durability and better performance. This results in rapid polishing slurry that achieves highly polished finishes on a variety of metals. Both alkaline and acidic slurries can be used with polishing pads. The polycrystalline alumina polishing slurry is an aqueous slurry of alumina in which the fundamental crystal size ranges from 50 to 100 nm.

Utilizing an abrasive platform that is able to contain the slurry may provide a better dispersion property in applications where spraying is not possible [21]. The material removal rate in slurry erosion is dependent on a large number of factors that are complex. However, it is generally agreed that the mechanism of material removal is one of abrasion by particles that impinge the surface at an acute angle with sufficient momentum to dig and form a groove.

The slurry concentration needs to be a proper ratio and constantly applied to the surface of the part. This ratio is typically 4:1 when mixed with water. The material removal rate not only depends on the suspension chemistry or density, but is also affected by several other factors. For instance, the material removal rate decreases significantly with increase in the pH of the suspension. The pH of suspensions depends on the abrasive properties and water chemistry. Ideally, the pH of the suspension should be between 6 to 7.

2.5 Hydrodynamic lubrication

In mechanical polishing, heat will be generated by the mechanical abrasive action. Liquid cooling may achieve higher thermal conductivity than air cooling. A suitable coolant would have favorable properties such as high thermal capacity, low viscosity, chemically stable and non-toxic. Coolants in liquid or gas form have different specific latent heat of

condensing phase change and enthalpy of vaporization. Water is the most common coolant. Its high heat capacity and low cost makes it a suitable heat-transfer medium.

Compared with other types of fluid, water has high specific heat capacity at room temperature and atmospheric pressure. This allows water to have a more efficient heat transfer over distance with low mass transfer rate. Deionized water has low electrical conductivity (purer), is more environmentally friendly and less hazardous as compared to chemical-based coolants. In addition, water would be useful in purging out the fine debris and fragmented abrasive grains, keeping the disk and workpiece surface clean.

Material removal rate is sensitive to the tool speed, slurry viscosity and abrasive surface roughness under the semi-contact condition. The material removal rate will first increase then decrease due to the film thickness reduction or abrasive roughness increase [22]. The main reason for the undesirable effect of surface texturing may be that the hydrodynamic pressure effect is inadequate at low vibration velocity amplitude and varies under different lubrication conditions [23].

Surface roughness has been found to be a crucial parameter influencing the lubrication of sliding contacts. The correlation of mechanical wear with roughness and lubrication factors indicate that abrasive conditions may also be influenced by the lubricant.

Hydrodynamic theory was developed within the field of tribology. Reynolds' theory had been known for the theory of hydrodynamic lubrication. Polishing in dry condition have shown increased surface roughness and hardness of parts. Similar theories such as thermo-hydrodynamic lubrication and turbulent hydrodynamic lubrication are also based on Reynolds' foundation.

A lubricating film separates the surfaces from direct contact and it in general reduces friction and sometimes abrasive disk wear, since friction within the fluid is less than between the directly contacting surfaces. The sliding speed has to be higher to generate a thicker film. A higher viscosity leads to a thicker lubricant film. It is noted that the hydrodynamic friction will increase with the increase of both sliding speed and viscosity.

2.6 Closing remarks

The summary of literature survey identified several problems associated with the existing polishing methods and the need to conduct this thesis work. The general information on polishing mechanisms has been presented and the conditions influencing the surface texture are described. Due to the current processes that lack certain capability necessary to meet specific objectives, a new polishing method is thus needed to fulfill the following requirements simultaneously:

- (1) Achieve a specific roughness according to industry standard;
- (2) Eliminate scallop height defect and prevent induced defects;
- (3) Maintain thickness of edges within dimensional tolerance;
- (4) Keep the surface cool and clean throughout the process.

The proposed random-orbital tool setup and approach, including the four types of conditions and abrasive grit sizes will be presented in chapter 3. The methodology and the type of metrology equipment used for evaluating the fan blade surface topography will be explained in chapter 4. Results of the polished samples including abrasive disk life evaluation will be discussed in chapter 5. Finally, conclusion will be summarized in chapter 6 and future work proposed in chapter 7.

3. Proposed approach

Random-orbital polishing is proposed as a new method in which experimental trials will be performed on actual fan blade components. The results from random-orbital polishing will be assessed and compared with the existing rotary polishing process.

Figure 4 shows the prototype random-orbital tool before and after modification. The replacement parts were purchased off the shelf and were compatible with the interconnecting parts of the tool. Figure 4(a) reveals a flaw in which air could escape through the gap between the open-edged shroud and the pad, assuming that a constant supply of air was flowing through the port. Figure 4(b) addresses this flaw by means of replacing the existing shroud with a different assembly comprising of a rectangular air funnel and closed-edge shroud.

These parts were identified from another model with dust extraction features which were found compatible with the original tool by means of direct bolt-on. Upon fitment of the replacement parts, the gap between the shroud and the pad was closed. With this improved design, air would be able to flow directly inward and out through the holes of the abrasive disk.

Figure 4. (a) Before modification - original random-orbital tool with a circular port and shroud cover (open gaps indicated by the black arrows), and (b) after modification - components of the random-orbital tool with a rectangular air funnel and shroud (closed gap and funnel indicated by the black arrows).

3.1 Random-orbital polishing

Random-orbital tools combine the speed and aggressiveness of a belt polisher with the ability to produce a finer finish and are significantly different in operation as compared to rotary polishing tools. The orbital motion causes the disk to rotate in a circle and at the same time the disk oscillates in an eccentric pattern inside this larger, main rotating pattern. The backing plate not only spin in a circular motion around its axle but has an off-center backing plate connection that generates the vibration amplitude in small ellipses.

Figure 5(a) shows a picture of the prototype random-orbital tool after modifications were made to it. The random-orbit motion depends on the ratio between the orbital radius and the radius of the disk rotation. Inertia causes the disk to want to rotate in unison with the orbital motion, but friction with the specimen tempers this motion, and causes the disk to speed up, slow down, or even turn backward. The reason it is called random is because the spinning is controlled by the free-floating spindle that will stop spinning if enough pressure is applied to the backing plate. This drive mechanism on the spindle includes a clutch which will allow the pad to stop rotating when too much pressure is applied on the surface. Figure 5(b) shows the exposed floating spindle, viewed from the bottom of the tool with pad removed.

Figure 5. (a) Prototype design of the random-orbital tool with integral cold air (indicated by the black arrow) and water (indicated by the white arrow), and (b) free-floating spindle rotates in anti-clockwise position during activation.

Figure 6(a) shows the primary motion of an eccentric orbit and the second motion in figure 6(b) is the rotation of the disk about the disk's center. The abrasive disk is eccentric to the machine center, as well as its path of rotation. Figures 6(c), 6(d) and 6(e) show the combined motions in which the tool path traces out a geometric shape that resembles a shape of a roulette or spirograph. The 2 mm diameter orbit in figure 5(e) is selected for the experimental trials due to its ability to produce a fine surface finish.

Figure 6. (a) Primary motion by circular-orbit, (b) secondary motion by single rotation, (c) random-orbit motion – coarse, 10 mm diameter orbit, (d) random-orbit motion – medium, 5 mm diameter orbit, (e) random-orbit motion – fine, 2 mm diameter orbit.

3.2 In-line air cooling by cold air gun system

A cold air gun has been used in the setup for accurate spot cooling. The vortex tube inside the cold air gun is also known as the Ranque-Hilsch tube shown in figure 7 [24]. The gas emerging from the "hot" end can reach temperatures of 200 °C, and the gas exiting the cold nozzle can reach −50 °C. Pressurized air is injected tangentially into a swirl chamber and accelerated to a high rate of rotation.

Due to the conical nozzle at the end of the tube, only the outer shell of the compressed gas is allowed to escape at that end. The remainder of the gas is forced to return in an inner vortex of reduced diameter within the outer vortex. The phenomenon of the vortex tube is the temperature separation between the cold vortex core and the warm vortex periphery.

Figure 7. The working principle of a cold air gun or Ranque-Hilsch tube [24].

3.3 Overview of the system

A standard cold air gun system (ExAir model 5215) with a single outlet is used. As shown in figure 8, the cold air gun generates two streams at different temperature from a single compressed injection. The cold air gun separates the compressed air into two opposite directions, where hot air is exhausted from the rear end and forcing the cold air at the front end due to the lowered pressure gradient at the cold section [25]. The cold air gun is continuously activated for each section of specimen.

By adjusting the incoming air pressure at the regulator at 620 kPa, the cold air gun maintained an air pressure of 300 kPa in-line, and 172 kPa at the outlet port to the tube. The rate of cold air flow escaping out of the abrasive disk holes is measured at 1.0 m/s using a standard anemometer.

Figure 8. Functional diagram of the experimental setup showing the principle operation of the cold air gun connected in-line with the random-orbit tool.

4. Experimental methodology

In practice, rotary polishing is accepted as the most common method to remove surface irregularities and to achieve a uniform finish. Geometrical features and texture parameters of a properly polished surface depends on the selection of the polishing method for the target workpiece material. The analytic work assigned for this study compares the measured surface textures and features of aluminum fan blades processed by four conditions of random-orbital polishing and one condition of rotary polishing.

4.1 Specimen preparation

The workpiece material of the fan blade specimens is made from aluminum alloy 7255-T7751. All specimens have similar scallop height features at the leading edge. The material composition is shown in Table 1.

Table 1. 7255-T7751 Aluminum alloy maximum composition limits (% weight).

Specimen	Alloying Elements									
7255-T7751 Alloy Material	Zn	Cu	Mg	Zr	Mn	Cr	Ti	Si	Fe	Al
	8.4	2.6	2.3	0.15	0.05	0.04	0.06	0.06	0.09	remainder
	Others: 0.05									

Figure 9 shows the polishing plan for all conditions, 1 to 4: P120 grit for section 1, P180 grit for section 2, P240 grit for section 3, P320 grit for section 4 and P400 grit for section 5. For wet conditions 2 and 4, deionized water with average pH of 7.4 at 23 °C is triggered by the valve at every 3-minute interval. For cold air conditions 3 and 4, the cold air gun is started-up for 3 minutes until the air temperature dropped to a minimum of 15.5 °C. At the end of the trials, the parts are verified for dimension conformity where the leading-edge thicknesses are measured using a digital dial indicator Mitutoyo 543-400B. The fifth specimen for the rotary polishing method is not shown in this figure. Polishing parameters for both methods are shown in Table 3.

Figure 9. Polishing plan of the random-orbital trials for four specimens and four conditions. Each specimen consists of 5 sections with 5 different grit sizes per section. Grit sizes are P120, P180, P240, P320 and P400. The four conditions are; condition 1 (dry, ambient air); condition 2 (wet, ambient air); condition 3 (dry, cold air) and condition 4 (wet, cold air).

4.2 Abrasive selection

Aluminum oxide (Al_2O_3) has a Mohs value of 9. This strength enables the abrasive to be slowly dulled and hard to fracture, making it suitable for polishing. The abrasive disks are supplied by VSM abrasives (part number KK712J), and each disk used for the random orbital tool measures 127 mm in diameter with holes to allow air and water to pass through. For the rotary polishing tool, the abrasive disk measures 102 mm in diameter with no holes. A total of five grit sizes (P120, P180, P240, P320 and P400) are selected for the random-orbital trials. The grit classification has been established by the association of European abrasive manufacturers (FEPA) where P is the international standard of the FEPA. The grain size of the abrasive grit number is shown in table 2.

Table 2. Grit number and corresponding grain size according to FEPA (Europe).

Grit Number	Grain Size (μm)
P120	127
P180	78
P240	58.5
P320	46.2
P400	35

Figure 10(a) shows the abrasive disk without holes, used for rotary polishing, while the abrasive disk with holes is shown in figure 10(b). The holes serve as ventilation ports to allow water and air to flow out of the tool, in a downward direction. Figure 10(c) shows the polishing pad, comprising of soft density foam material to allow flexibility under polishing load. This helps to make positive contact with the free-form contour of the fan blade specimen.

Figure 10. (a) Abrasive disk without holes for rotary polishing, (b) abrasive disk with holes for random-orbital polishing, and (c) polishing pad made of soft density foam.

4.3 Polishing process and temperature measurement

In figure 11(a), a plastic squeeze bottle sprays deionized water on the surface at 3-minute intervals over a total process time of 9 minutes. The random-orbital method uses a dual-axis Dynorbital® tool (model number 57583). Figure 11(b) shows the random-orbital tool with in-line air-cooling and water spray.

The thermal images of the abrasive disks during the polishing cycle indicate an elevated temperature of approximately 82 °C, from initial ambient temperature. The bright, orange-yellow spectrum indicates a relatively hot signature. From figure 11(b) thermal images of the abrasive disks during the polishing cycle show that the temperature can be lowered to approximately 15 °C by mixing cold air with water. The darker, purple-blue spectrum indicate the colder region where the water and air are applied to the surface.

The air pressure setting for the tool is fixed at 620 kPa and controlled by an in-line air pressure regulator. The tool speed setting is set at maximum of 10,000 rpm by a knob. The rotary polishing method uses a single-axis tool, Toku model TAG400 with an abrasive disk of P320 grit size.

Figure 11. (a) Rotary polishing method by single-axis rotary tool with external spot cooling with a plastic bottled water and (b) random-orbital tool with in-line cold air and deionized water.

The 9-minute process time is a standard operating procedure established by the rotary polishing method. Therefore, the experimental plan follows this fixed standard time. All specimen sections are polished in stationary condition with approximately 50% of the abrasive disk diameter (126 cm^2) making contact to the leading-edge surface and the remaining 50% over-hang. This is because of the curvature of the fan blade and flexibility of the backing pad limit the full contact surface. The backing pad is made of foam, and its soft density ensures conformal contact between the abrasive disk and leading-edge surface

The random-orbital tool is set at a fixed speed of 10,000 rpm by an adjustable knob, and the disk is kept in motion by depressing the lever with the index finger. The tool load is measured to be approximately $3.485 \pm 0.1 \text{ kgf}$. If the load exceeds 4.8 kgf , the tool will stop rotating. This is due to the safety design limit of the internal motor shaft balancer and bearing, which is important in ensuring that the polishing load is maintained below this value. Manual polishing is performed by a single operator who will be careful not to apply excessive force and only to support and maintain the tool upright. Therefore, the actual load maintained in the process is assumed to be $3.485 \pm 0.1 \text{ kgf}$.

Table 3. Table of parameters for the experimental conditions.

Method	Polishing parameters			Deionized water parameters
Rotary polishing	Spindle speed n = 12,000 RPM	Supply air pressure = 620 kPa	Process time = 9 mins	pH = 7.4 Conductivity = 21.7 μ S/cm Temperature = 23 °C
Random-orbital polishing	Spindle speed n = 10,000 RPM	Supply air pressure = 620 kPa	Process time = 9 mins	pH = 7.4 Conductivity = 21.7 μ S/cm Temperature = 23 °C
Method	Cold gun parameters	Abrasive disk		
Rotary polishing	N/A	Material = Aluminum Oxide Al ₂ O ₃	Grit Size = P320	Diameter = 102 mm (without holes)
Random-orbital polishing	Inlet air pressure = 300 kPa Temperature = 15.5 °C	Material = Aluminum Oxide Al ₂ O ₃	Grit Size = P120, P180, P240, P320, P400	Diameter = 127 mm (with holes)

4.4 Cold air gun setup

The cold air gun shown in figure 12 is a portable vortex tube that has a magnetic plate to easily mount flat onto the metal backwall of the downdraft booth. In order to verify how long it takes for the cold air to reach its lowest possible temperature, a simple measuring instrument is setup for this test. A thermocouple with the cold air gun nozzle is inserted inside a polypropylene bottle in order to encase the air and prevent external variation in heat to affect the result.

A quick assessment was carried out by using a digital temperature recording instrument for studying the temperature change over a period of time. Three available air hoses of

varying material, internal diameter and wall thickness were tested. 620 kPa of air pressure was supplied to the system and the temperature measurements were recorded in-line from each hose tested.

Figure 12. (a-c) Initial setup testing of the cold air gun temperature with a digital temperature recording instrument, and (d-f) comparison of various hose sizes and the different temperature values generated.

Figure 13 shows the results of the temperature variations between the three different air hoses. The test duration was dependent on the performance of the cold air gun, in which the temperature of the air ultimately reaches its saturation point. Upon completion of the tests, all the hoses show similar trend where gradual descents were observed from 100 seconds to 180 seconds, with small displacements in temperature variations between them.

Results show that the 9 mm hose produced a temperature marginally lower than the rest after 140 seconds, reaching 3 °C. However, the 6 mm hose has the fastest drop in temperature from 0-60 seconds. The 3 mm hose, has the largest disadvantage at mid-

range of time but after 150 seconds, temperature stabilizes to within 3 °C and the difference is almost negligible as compared with the other two types of hoses. In summary, the 9 mm hose was selected for the experimental trials. In addition, this hose had a thicker outer layer, allowing better insulation to maintain optimum air temperature throughout the polishing process.

Figure 13. Results of the air temperature changes over a period of time.

4.5 Surface characterization

4.5.1 Roughness measurements

The Zeiss Smart Zoom 5 digital microscope is used to examine the general condition of the specimen surface after polishing. The main purpose is to examine for induced tool defects such as swirl lines or scratch marks. The switchable ring-light on the microscope enabled viewing of these deviations by using intensity variations.

The Talysurf CCI 3000 coherence correlation interferometry (CCI) is used for detailed measurement of 2D and 3D surface roughness and furrow parameters in accordance with ISO 4287 and ISO 25178 respectively. The strategy is to have the measurements in the transverse direction to the tool lines which would be the direction that will give the

maximum height parameters. The imaging system is “traversed” through its range by the piezo drive system, thus, the focal point is noted for each pixel in the CCD array. For 2D roughness measurement, three profiles are extracted for each sample; while two repeats are performed for 3D roughness measurement.

The lateral resolution is configured to 1024 x 1024 pixels. The specimen is mounted at normal incidence angle to the optical lens in order to capture an accurate pattern. This allows the camera to detect the fringe pattern macro as the scan range needed to fully cover the height of the surface. The stand-off distance between the lens and the specimen is approximately 4.7 mm.

Parameters for auto-stitching mode is optimized to match offset and tilt. The XY scanning area is a 3 X 3 square grid (9 squares, single level) with 20% field-of-view (FOV) and 2.0 μm Z-overlap. The 9 squares stitched together to form a total area of 6.45 X 6.45 mm (41.60 mm²) for the areal measurement, as shown in figure 14(a). The image of the initial a-machined condition reveals an array of undulating scallop height features perpendicular to the machining feed direction, as shown in figure 14(b).

Figure 14. (a) CCI measurement showing X-Y scanning area and direction, (b) initial as-machined specimen surface showing scallop height features.

4.5.2 Statistical functions

Detailed characterization of surface texture features is necessary to understanding the relationships between various polishing methods. The Fast Fourier Transform (FFT) spectrum is used to analyze the spectral components of the surface by displaying patterns to show up periodicities and orientations. Each point in the spectrum corresponds to a frequency and its colour indicates the amplitude of this frequency. The surface may contain periodicities in the X and Y direction, generating useful information about the magnitude and phase of each wavelength.

Power spectral density function (PSD) analysis is useful for studying the weights of various periodic components in a surface profile. It decomposes the measured surface texture geometry into different components of spatial frequencies using Fourier transforms and provides more information than single-value parameter such as *Ra* [26]. Instead of graduating the horizontal axis in frequencies as compared to standard FFT spectrum, PSD inverts the horizontal axis and thus proposes a linear reading of the wavelengths to gain a better understanding.

4.6 Metallurgical testing

After the polishing process, the thicknesses of the polished sections are measured using a digital dial indicator Mitutoyo 543-400B. The cross-hair lines are marked at 25 mm distance perpendicular from the leading-edge section. Next, metallurgical examination is used to analyze the cross-section of the polished samples. A precision cutting wheel is used for this task and operated at 3,000 rpm with a feed-rate of 15.2 mm/min and are later processed in a hot mounting machine with phenolic resin. Buehler Ecomet 300 grinding machine is used to lap the sample mounts with 3 μm and 0.05 μm diamond suspension under 5 N force. Keller's etchant by swab method is used to reveal the surface details by Olympus microscope BX53.

4.7 Micro-hardness testing

Hardness testing of the polished samples is performed using a Vickers indenter (Falcon 250 Innovatest) with a diamond pyramid tip as shown in figure 15. The hardness tester and procedures are performed according to the standard test methods of ASTM E92-82 and ASTM E384. An average of three hardness indentation readings are taken by applying a load of 300 gF (2.94 N) and a dwell time of 10 seconds at the center of the sample area.

Figure 15. Vickers hardness testing with an average of 3 indentations.

4.8 Abrasive disk characterization

Studying the abrasive disk life for the various conditions by the random-orbital method can be used to determine the required number of consumables needed. Furthermore, for wet conditions, it is important to determine the quality of the abrasive disk in terms of wear and cleanliness.

A high precision Ohaus PX323JP model analytical weighing balance is used to measure the weight loss of the abrasive disk after polishing. Before weight measurements, the abrasive disks are cleaned by a pneumatic gun for approximately 3 minutes and until no visible traces of loose dust or water are present on the abrasive disk surface. Then, a section of each abrasive disk measuring approximately L10 mm X W10 mm is cut out and inspected by digital microscope using dino-lite edge model number AM7915MZTL.

5. Results and discussion

5.1 Influence of process conditions on surface roughness

The microscopic image of the initial condition is represented in figure 16(a) and the lay can be clearly seen on the surface. Figure 16(b) shows the post-polished surface after rotary polishing method. The rotary polishing method exhibited signs of fine tool lines on the surface in a circumferential pattern. Figures 16(c) to 16(f) presents the random-orbital polished samples, where a clear distinction can be made between wet and dry conditions.

Three distinct groups of surface textures are classified for clear identification: group 1 - matte with anisotropic finish resulting on rotary polished sample shown in figure 16(b), group 2 - shiny with fine scratch marks in cross-hatched circular pattern shown in figures 16(c) and 16(e), group 3 - satin with isotropic non-directional finish and homogeneous, resulting on wet orbital polished samples depicted in figures 16(d) and 16(f). All methods under all conditions can remove the sharp-peaked scallop height features.

The rotary and random-orbital tool are successful in the removal of scallop height features. For dry conditions shown on figure 16(c) and 16(e), the fine scratch marks appear to be shiny in nature, which is an indication that the abrasive grains have not contacted the surface valleys.

Figure 16. Microscopic images before and after polishing with P320 grit size: (a) Initial, as-machined condition with scallop height features, (b) Existing polishing method showing an even distribution of circumferential marks on the surface (c) Random-orbital method for condition 1 showing cross-hatched marks on the surface (d) Random-orbital method for condition 2 showing a uniform surface texture, (e) Random-orbital method for condition 3 showing cross-hatched marks on the surface (f) Random-orbital method, condition 4 showing a uniform surface texture. Measurement instrument used is Zeiss Smart Zoom 5 digital microscope.

As presented in chapter 1.4, the surface roughness parameters have to fall within the target range as part of the technical criteria. Figure 17 shows the trend of mean surface roughness (Ra) across the selected grit sizes for random-orbital polishing. The target (ideal) values are, Ra between 0.8 to 1.0 μm and Rz between 5.0 to 6.0 μm . In comparison to rotary polishing, random-orbital polishing for all conditions produce lower Ra values. Condition 1 produces the lowest Ra value.

Results of varying grit size indicate that conditions 2 and 4 produce higher Ra than conditions 1 and 3. Overall, all the specific grit sizes for conditions 1 and 3 produce an Ra of below 0.8 μm , which is not ideal. Moreover, conditions 1 and 3 produce the lowest Ra values as compared with condition 2 and 4. Three grit sizes for conditions 2 (P320 and P400) and condition 4 (P320) produce ideal Ra values between 0.8 and 1.0 μm .

Figure 17. Results of mean surface roughness (R_a) for all conditions with P120, P180, P240, P320 and P400 abrasive grit sizes. Measurement instrument used is Talysurf CCI 3000.

In figure 18, the maximum height profile (R_z) for all conditions by random-orbital polishing are lower than rotary polishing, except for condition 2. Results of varying grit size indicate conditions 2 and 4 produce higher R_z than conditions 1 and 3. Conditions 1 and 3 produce the lowest R_z values as compared with condition 2 and 4. Condition 3 generates the lowest R_z value which is not ideal. Condition 4 generates a higher R_z as compared to the initial surface. P320 grit size for condition 4 produces ideal R_z value of 5.8 μm , thus making it a potential candidate which fulfills both R_a and R_z requirements simultaneously.

Figure 18. Results of maximum height profile (R_z parameter) for all conditions with P120, P180, P240, P320 and P400 abrasive grit sizes. Measurement instrument used is Talysurf CCI 3000.

The S_a parameter is the arithmetic mean deviation of the surface which provides a detailed interpretation and comparison of the surface texture. As mentioned in chapter 1.4, the target (ideal) values for S_a is between 1.0 to 1.8 μm . In figure 19, it can be observed that conditions 1 and 3 produced a lower S_a value as compared to the initial value. Condition 3 produces the lowest S_a value. Condition 2 produced a S_a value marginally higher than the initial value after polishing ($\Delta 0.1 \mu\text{m}$).

Figure 19. Results of mean height (S_a parameter) with P320 abrasive grit size. Measurement instrument used is Talysurf CCI 3000.

Figure 20 shows the results of the areal peak-to-valley heights (S_z) for random-orbital polishing. As mentioned in chapter 1.4, the target (ideal) values for S_z is between 9.0 to 15.0 μm . All random-orbital polishing conditions produce lower S_z values as compared with rotary polishing. Condition 1 produces the lowest S_z value, indicating the lack of height for the coating adhesion to be effective. Conditions 1 and 3 show potential in producing similar profiles, both with values significantly lower than the initial value. Conditions 2 and 4 have a higher S_z value than 1 and 3, but both lower than values produced by rotary polishing.

Based on manufacturing know-how and past experiences, the ideal values indicated by the target range can be further elaborated. The following are some expected consequences if the S_z values fall out of the upper or lower limits:

1. S_z below 9.0 μm – post-processing such as coating may fail adhesion test as a result of the surface being too smooth;
2. S_z above 15.0 μm – post-processing such as coating may fail aesthetic quality due to striations penetrating the coating layer.

Figure 20. Results of maximum surface height (S_z parameter) for all conditions with P320 abrasive grit size. Measurement instrument used is Talysurf CCI 3000.

Table 4 shows a summary of the roughness measurements for both polishing methods with P320 grit size, including furrow data. Values of post-processes by shot peening and vibratory finishing are shown as references. The target (ideal) values, Ra between 0.8 to 1.0 μm and Rz between 5.0 to 6.0 μm , are associated with vibratory finishing at final processing. Random-orbital polishing with condition 4 using P320 grit size achieved both the ideal Ra and Rz values simultaneously. This means that the surface texture produced by this condition and grit size, although not identical, correlates to vibratory finishing since both processes utilize vibratory mechanism.

The R_{sk} or S_{sk} parameter (skewness) can be used beneficially to understand the shape of surface texture height distribution. For a surface which meets Gaussian distribution and has a symmetrical profile, its S_{sk} value equals to 0. This parameter may determine the presence of sharp features on the surface. The positive value of skewness (S_{sk} , initial condition = 0.35) means comparatively more sharp peaks and rounded valleys; while the negative value of skewness (S_{sk} , random-orbital polishing = -1.4 to -0.3) indicates a majority of rounded peaks and sharp valleys for the random-orbital polished surfaces.

S_{ku} (kurtosis) parameter can be used to characterize the spread of the height distribution. For a surface which meets Gaussian distribution, its S_{ku} equals to 3; for a centrally distributed surface, its S_{ku} is typically larger than 3; whereas for a surface meeting well-spread height distribution, its S_{ku} is smaller than 3, as found in as-machined value of 2.67. The kurtosis value for rotary polished surface (S_{ku} , rotary polishing = $6.68 > 3$) and similarly for random-orbital polishing (all conditions) the values indicate more distribution tails; while the S_{ku} for random-orbital polishing for conditions 2 and 4 is nearer to 3, indicating that the surface textures are close to having normal distribution.

According to furrow parameters, condition 1 produced the lowest maximum depth, while condition 2 produced the highest maximum depth. Condition 2 produced the highest mean depth; while condition 3 produced the lowest mean depth. Condition 4 produced the highest mean density. The mean depth and density in condition 4 resembles the values that are closest to that produced by vibratory finishing.

Table 4. Surface characterization parameters for all processes from machining to vibratory finishing.

<u>Process</u>	<u>CNC Milling</u>	<u>Rotary Polishing</u>	<u>Shot Peening</u>	<u>Vibratory Finishing</u>
<u>Condition</u>	<u>As-machined</u>	<u>Wet</u>	<u>Semi-final</u>	<u>Final</u>
<u>Height parameters</u>				
<i>Ra</i> (μm)	0.90	1.05	2.11	0.99
<i>Rz</i> (μm)	4.30	6.06	8.83	5.69
<i>Rsk</i>	-0.04	-0.84	-0.15	-0.94
<i>Rku</i>	1.76	2.71	1.54	2.52
<i>Sa</i> (μm)	1.20	1.31	1.86	1.18
<i>Sz</i> (μm)	9.41	18.06	13.24	9.09
<i>Ssk</i>	0.35	-0.34	-1.09	-1.72
<i>Sku</i>	2.67	6.68	3.68	5.68
<u>Furrow parameters</u>				
<i>Max. depth</i> (μm)	4.94	17.64	11.85	8.85
<i>Mean depth</i> (μm)	2.14	3.42	2.21	1.36
<i>Mean density</i> (cm/cm^2)	903.12	1126.82	892.77	2206.07

<u>Process</u>	<u>Random- Orbital Polishing</u>	<u>Random- Orbital Polishing</u>	<u>Random- Orbital Polishing</u>	<u>Random- Orbital Polishing</u>
<u>Condition</u>	<u>1: Dry</u>	<u>2: Wet</u>	<u>3: Dry, Cold Air</u>	<u>4: Wet, Cold Air</u>
<u>Height parameters</u>				
<i>Ra</i> (μm)	0.32	0.97	0.34	0.82
<i>Rz</i> (μm)	3.95	6.93	3.83	5.86
<i>Rsk</i>	-1.53	0.14	-2.03	-0.84
<i>Rku</i>	9.56	3.13	13.07	3.45
<i>Sa</i> (μm)	0.36	1.34	0.35	0.98
<i>Sz</i> (μm)	8.85	16.86	8.93	15.59
<i>Ssk</i>	-1.18	-0.61	-1.40	-0.30
<i>Sku</i>	9.90	3.87	10.72	4.38
<u>Furrow parameters</u>				
<i>Max. depth</i> (μm)	3.89	9.18	3.98	5.85
<i>Mean depth</i> (μm)	0.69	2.34	0.56	1.51
<i>Mean density</i> (cm/cm^2)	1124.72	1120.09	1125.91	1132.34

5.2 FFT and PSD analyses of the rotary and random-orbital polished surfaces

Based on Fourier analysis, surface texture is assumed to be composed of a series of sine waves with different frequencies and amplitudes. PSD is a measure of the amplitude of each harmonic part for a specific frequency and along a given direction. Thus, for 3D surface texture, the PSD plot emerges as colour-scaled function values upon an X–Y plane. The magnitude of PSD (displayed on the Z-axis) represents the amplitude of the sine wave at a specific spatial frequency for a given direction. In addition, it could average all X or Y profiles' PSD to obtain the PSD values along only the X or Y direction. Mathematically, the PSD is defined as the square of the Fourier transform of the measured surface texture and is expressed as [26]:

$$\text{PSD}(f) = \frac{d_0}{N} \left| \sum_{j=1}^N Z_j \cdot \exp[-i \cdot 2\pi f(j-1)d_0] \right|^2 \quad \text{Eq 5}$$

where $i = \sqrt{-1}$; d_0 is the sampling length; Z_j is the surface amplitude function; the spatial frequency f equal to K/L , where K is an integer that ranges from 1 to $N/2$; N is the number of sampling points over a finite length L of surface errors.

Figure 21 illustrates the statistical function results of the surfaces by using coherence correlation interferometry (CCI). Figure 21(a) shows the FFT magnitude of the rotary polished surface; its average profile PSD profile along the Y direction, as shown in figure 21(c), fluctuates with respect to the spatial frequency, and the trend shows a monotonic descent. Figure 21(b) shows that the FFT magnitude of the random-orbital polished surface (condition 4, P320 grit size) is generally much smaller (-48.7 dBc) than that of rotary polished surface (-66.5 dBc). The unit in dBc is decibels relative to the carrier.

Figure 21(d) shows the average PSD along the Y direction having a spatial frequency which is relatively flat (horizontal) at the beginning and gradually descends at $1.0\text{E-}02$. A number of spikes in the curve indicate that there are high-frequency harmonic components along the Y direction. This could be due to the random motion of the abrasive grains in the polishing disk. By comparing results in figures 21(a), 21(b), 21(c), and 21(d), it can be seen that FFT and PSD characteristics differ significantly between

rotary and random-orbital surfaces; it shows that PSD could be a perceptive way to differentiate surface textures produced by different polishing methods.

Figure 21. Comparison of FFT and PSD for rotary and random-orbital polished surfaces. (a) FFT plot of the rotary polished surface, (b) FFT plot of the random-orbital polished surface, (c) Average PSD along Y of the rotary polished surface and (d) Average PSD along Y of the random-orbital polished surface.

Further analysis was carried out to investigate whether random-orbital polishing portray any similar characteristics to vibratory finishing. Figure 22 shows the FFT and average PSD along the Y direction for the two methods. The FFT magnitude of -48.7 dBc by random-orbital polished in figure 22 (a) is quite similar to vibratory finished surface with magnitude of -45.3 dBc in figure 22(b), with a marginal difference of 3.4 dBc. The average PSD along the Y direction for both methods shown in figure 22 (c) and figure 22(d), have similar curve profiles, except for a steeper gradient on the descent (in the range between $1.0\text{E-}02$ and $1.0\text{E-}01$) for vibratory finishing method.

Figure 22. Comparison of FFT and PSD for random-orbital polished and vibratory finished surfaces.

Contrary to the standard FFT spectrum with the x-axis graduated in frequencies, the spectral content could be represented in wavelengths (X-axis) and amplitudes (Z-axis). The study inverts the horizontal axis ($\lambda=1/f$) and thus proposes a linear reading of the wavelengths. The vertical axis displays the amplitude to a power of 2. However, this inverted axis creates a problem where the wavelengths found in the spectrum are not regularly spaced out anymore. The hanning window function was used to eliminate stray spectral lines in the Fourier transform modulus, making it possible to detect smaller spectral structures and also to improve texture direction results.

In figure 23, it can be seen that the peak amplitudes for random-orbital polishing (2.08 μm) in figure 23(a) and vibratory finishing (2.07 μm) in figure 23(b) are almost identical, with a small difference of 0.0077 μm . A possible explanation for this is the presence of water in condition 4 and vibratory finishing. In order to make a more detailed comparison, the slurry properties for condition 4 will be analyzed and discussed in chapter 5.9. The rotary polished surfaces in figure 23(c) differed significantly in contrast to the other methods, with a peak amplitude of 23.1 μm . A number of spikes in the curves for random-orbital polishing and vibratory finishing are observed; while rotary polishing only produced a single peak point. This shows a close relationship between the cutting mechanisms of both random-orbital polishing and vibratory finishing.

(23a) Random-orbital Polishing: Condition 4

Information		
Zoom factor	x4	
Smoothing	None	
Parameters	Value	Unit
Wavelength	0.0367	mm
Amplitude	2.0814	μm

(23b) Vibratory Finishing

Information		
Zoom factor	x4	
Smoothing	None	
Parameters	Value	Unit
Wavelength	0.0122	mm
Amplitude	2.0737	μm

(23c) Rotary Polishing

Information		
Zoom factor	x4	
Smoothing	None	
Parameters	Value	Unit
Wavelength	0.0092	mm
Amplitude	23.1628	μm

Figure 23. PSD amplitudes for (a) random-orbital polished, (b) vibratory finished and (c) rotary polished samples.

5.3 Summary of FFT and PSD analyses

PSD provides a more reliable description to the topography than the roughness and imparts several useful information of the surface. The spikes in the curve indicate that there are high-frequency harmonic components due to the random array of media indentation by polishing. The roughness shown in the frequencies play dominant roles in the surface roughness where it is associated with cutting mechanism [27].

The results of PSD colour spectrum indicate that random-orbital polishing (condition 4) has similar magnitude to that of vibratory finishing; whereas in comparison to the rotary polishing method, the magnitude and shape of its spectrum differs significantly. Similarly, the averaged PSD amplitudes show a strong correlation between the random-orbital polishing (condition 4) and vibratory finishing.

Since Fourier analysis represents surface roughness in a series frequencies and amplitudes, it can therefore be said that the data presented indicate that both random-orbital polishing and vibratory finishing produce similar roughness topographies. This is important because the ideal roughness values are based upon the target values by vibratory finishing process, which the random-orbital method has achieved.

5.4 Effect of cold air and water on the specimen and abrasive disk

In general, surface analysis by visual inspection is rather subjective and provides a less quantitative evaluation. However, the fan blade manufacturing process is heavily reliant upon the inspector's visual skill, experience and judgement in verifying post-polishing quality. The first type of surface irregularity that is commonly picked up by the visual inspection is the presence of scratch marks, gouges and furrows created by the polishing tool or abrasive. Therefore, it would be useful to perform a simple visual inspection on the samples after the trials, as a preliminary assessment before a full, detailed analysis.

In polishing mechanism, dislodged abrasive particles will start rolling between the surface of the disk and the workpiece, thus creating a series of furrows. A furrow is defined as depressions in the surface structure caused by mechanical abrasion. A surface

texture with higher furrow depth and density will promote better coating adhesion layer due to the enhanced anchoring effect in the structure.

It is possible to verify the effect of temperature between conditions 2 and 4, in order to understand why condition 4 shows evidence of furrows with less significant depths. The air stream in condition 4 may change the viscous flow in the sliding mechanism, thus affecting the rolling effect of the abrasive particles.

This phenomenon can be understood as furrows not caused by grooving action alone, instead, the distinct tracks are deepened by particles rolling over the surface due to the meniscus force of the water. It is the free moving abrasives present in the slurry that create swallow valleys in the surface, resembling that of three-body abrasion. The furrows are enhanced by the meniscus force produced due to the water surrounded by the abrasive [28].

In figure 24, random-orbital polishing shows evidence of grooving indicated by the furrow features produced on the surface structure. This is due to the hard-abrasive grain ploughing the aluminum alloy because of its ductile properties. The application of deionized water in conditions 2 and 4 is determined to be the key contributing factor that influences the surface texture. Conditions 2 and 4 (wet) have deeper, more prominent furrows as compared to conditions 1 and 3 (dry). Condition 2 produced the largest furrow depth at sparse locations randomly, which is not ideal. The texture of condition 4 appear to be homogenous as it has a better distribution of furrows on the surface at approximately 0.5 mm spacing distance. In summary, furrow properties are similar for conditions 1 and 3; while condition 2 shows localized, deep furrows and condition 4 shows a uniform distribution of furrows.

Figure 24. 3D images of random-orbital polished samples with P320 grit size: (a) Condition 1; dry, (b) Condition 2; wet, (c) Condition 3; cold air and (d) Condition 4; wet, cold air. Measurement instrument used is Talysurf CCI 3000.

Heat dissipation during the random-orbital polishing is important as it influences the abrasive disk life. An infrared camera is used to record the abrasive disk temperatures for each condition and the results are given in figure 25. For the existing method by rotary polishing, the temperature is recorded at 82°C after 9 minutes of polishing time. The average temperature of the random-orbital abrasive disk is recorded at 3-minute intervals from 0-9 minutes.

A method to visually inspect the quality of the abrasive disk after polishing is by colour comparison. The original crystalline form of aluminum oxide abrasive is corundum and its distinct colour is a mixture of deep reddish-brown. During the polishing process, it is imperative that the abrasive is maintained clean throughout for effective cutting action. Accumulation of debris on the abrasive can be identified by the greyish-white colour due to the residual particles of the parent material. Conditions 1, 2 and 3 show signs that the abrasive is affected by the accumulation of debris. This engulfment would dull the agglomerated abrasive structure, which reduces cutting effectiveness with the polishing time.

Figure 25 shows the abrasive disk temperature change over 9 minutes for P320 grit size. The images on the right show the corresponding condition and wear pattern on the abrasive disk at the end of the polishing cycle. The accumulation of debris (greyish-white colour) is clearly seen in conditions 1 and 3 of the abrasive surface. The greyish-white residue is likely from material removed from the specimen. Abrasive disk for condition 2 is generally clean (deep reddish-brown colour); while other areas show evidence of debris (greyish-white colour). The reddish-brown residue indicates that the disk has less particle loading. This implies that there is inhomogeneous water distribution within the disk. Abrasive disk for condition 4 is the cleanest as compared with the rest, signifying a homogeneous air-water distribution within the disk.

Condition 2 lacks of additional cold air and this creates a flood-coolant embodiment on the surface. It is important to note that a certain amount of wettability is crucial to ensuring cleanliness of abrasive disk, as proven in condition 4. All conditions operate at different temperature levels, and these variations do not provide significant evidence to justify its influence on the abrasive structure. However, elevated temperatures in mechanical polishing are known to cause thermal defects within the surface. Therefore, a lower operating temperature for polishing operation is preferred.

Adding air-cooling for condition 4 has shown a significant reduction in temperature by approximately 63 % as compared with condition 1 and 27 % as compared with condition 2. The understanding from condition 4 is that the abrasives must be moist and not

excessively wet, in order for better performance. In addition, the air stream removes the build-up of debris and keeps the surface clean.

Figure 25. Average relative temperatures measured by FLIR on the random-orbital abrasive disk at 3-minute intervals up to 9 minutes. Images taken by dino-lite edge microscope, model number AM7915MZTL.

5.5 Abrasive disk life evaluation

The abrasive disk life study is beneficial in determining process suitability of random-orbital polishing from a consumable requirement or cost perspective. Disk wear can be determined by weight measurements and final topography in order to determine the disk surface wear patterns [29]. A lower wear on the disk means that the disk life is higher. Disk wear was measured using different techniques, namely, (i) by disk weight change just before and after each trial, and (ii) by means of optical microscopy. Measurement purpose was to estimate disks' mass loss and wear pattern.

Figure 26 shows the abrasive disk life study in terms of weight loss measurements before and after polishing. Conditions 2 and 4 experienced the highest weight loss as compared with conditions 1 and 3 after polishing. For easy trend analysis of the different grit sizes, moving average trendline was used in the data plots. Condition 1 shows a steady, gradual

increase in weight loss from P120 to P400. Conditions 2 and 4 have similar values in weight loss with fluctuations across the grit size range.

Condition 3 has the most consistent trend overall, with an almost flat trendline. The spike in weight loss (also the highest value) for condition 2 at P320 could be attributed to the randomness of wear rate due to variations in the agglomerated grain structure when it interacts with water. The shape and direction of the recessed valleys in the structure may vary from disk to disk.

Figure 26. Abrasive disk life study by calculating the total weight loss after polishing. Measuring instrument used is Ohaus PX323JP model analytical weighing balance.

5.6 Microstructure analysis

The micrographs of the cross-sectioned coupons are shown in figure 27. All samples are examined under 500X magnification with white light and checked for evidence of distortion and defect in the surface structure. For conditions 1 and 4 in figure 27(a) and figure 27(d) respectively, there are no visible evidence of defects, which is acceptable by quality standards. In figure 27(b), condition 2 shows signs of uneven surface.

In figure 27(c), a gouge measuring approximately 25 μm in length and 5 μm in depth is observed in condition 3. These surface flaws depicted in conditions 2 and 3 are not desirable. Apart from these flaws, there are no additional surface distortion, strain lines and abrasive particle embedment on the specimens' surface for all random-orbital polishing conditions.

Figure 27. Microstructure of the random-orbital polished specimens (P320 grit size) cross-sectioned in the longitudinal direction: (a) Condition 1: Dry, (b) Condition 2: Wet, (c) Condition 3: Cold Air and (d) Condition 4: Wet, Cold Air. The images are captured by Olympus BX53 microscope.

5.7 Micro-hardness analysis

The hardness test results are shown in figure 28. The hardness values of all polished specimens under conditions 1, 3 and 4 are marginally higher than the as-machined condition. The single-axis rotary method has a highest increase in hardness by 12.2 HV, whereas the random-orbital polishing for condition 2 has an opposite effect with a reduction in hardness by 18.23 HV.

For the single-axis rotary polishing, the higher hardness can be attributed to the cutting speed of the tool, where the fixed direction generates a higher abrasive action. The increased hardness is attributed to the decrease in grain size and small particles of intermetallic compounds, while processed specimens submerged in water are known to exhibit lower hardness [30].

The water-cooled specimen for condition 2 shows lower hardness than the rest, suggesting that the meniscus force due to the surface tension of water between the abrasive disk and specimen has an effect on the hardness.

This effect is minimal for condition 4 because the water layer is disrupted by the continuous stream of cold air on the surface. Therefore, the surface tension for condition 4 is regarded as negligible as it neither creates any defect nor adversely affects the microstructure of the surface.

Figure 28. Micro-hardness test result for P320 grit size polished samples - average of 3 indentations for each condition carried out.

According to ISO 6507-1:2005, the Vickers (HV) hardness is calculated using the following formula:

$$HV = 0.1891 * \frac{F}{d^2} \text{ [N/mm}^2\text{]} \quad \text{Eq 6}$$

where d is the average of the two diagonals of the imprint and F is the applied load.

The yield stress (tensile yield) can be approximated from the hardness (HV) as follows:

$$\sigma_u = \frac{HV}{0.3} \text{ [MPa]} \quad \text{Eq 7}$$

Factoring in the hardness value of 178 HV and applying the formula in Eq 7, the yield stress σ_u for condition 4 is calculated as 593 MPa, which correlates to the original material specification of the fan blade specimen. It can be concluded that the overall hardness and strength for conditions 1, 3 and 4 is not significantly altered by random-orbital polishing.

5.8 Specimen thickness, cutting speed and material removal rate

The thickness of the polished sections of fan blade leading edge is measured using a digital dial indicator Mitutoyo 543-400B, shown in figure 29. The line markings are traced onto the fan blade surface and a cross-hair are drawn to intersect the lines at 25 mm distance from the leading edge of the fan blade.

Figure 29. Thickness measurement of the leading edge with a digital dial caliper gauge.

In order to remove the scallop height features and retain the specimen thickness within tolerance, the polishing method needs a lower material removal rate. Figure 30 shows the calculated cutting speed (V_c) based on the specimen thickness before and after polishing for a process time of 9 minutes. Condition 1 has the highest cutting speed for most grit sizes, hence a higher material removal rate. Conditions 2, 3 and 4 of grit sizes P320 and P400 have identical values which show uniformity in the cutting speed. P240 for these 3 conditions show similar uniformity but slight lower values by 0.0018 mm/min. A low cutting speed of 0.0026 mm/min may be insufficient to remove scallop height features on the initial surface.

In this analysis, condition 1 is considered unsuitable for polishing because of the cutting speed generated due to the absence of air and water loading. As a result, condition 1 may increase the likelihood in producing an under-thickness dimension of the fan blade leading edge. Therefore, P320 and P400 grit sizes for conditions 2, 3 and 4 are identified

as suitable candidates for random-orbital polishing in terms of good material removal control. Overall, the thickness height difference for random-orbital polishing is a small value of $\Delta 0.15$ mm, which is well within allowable stock material removal for the process. In summary, P320 and P400 grit size for conditions 2, 3 and 4 generate desirable cutting speed values and values are similar.

Figure 30. Random-orbital cutting speed (mm/min) calculated based on thickness height measurement of the specimen before and after polishing.

The most famous model is the Preston equation [31], which describes the linear relationship between the MRR and the product of the downforce P and relative velocity V , can be written as:

$$MRR = kPV \quad \text{Eq 8}$$

where k is an empirical constant based on experimental data. P , V , and MRR have an average value. The Preston equation mainly considers the mechanical action and the MRR . Therefore, it has some limitations. In fact, P and V may have a nonlinear relationship with MRR under some conditions. The time dependence on the removal rate may be described by a more precise Preston equation [32]:

$$MRR = kPVt \quad \text{Eq 9}$$

A higher speed may be considered to imply a larger centrifugal force for the slurry and a larger hydrodynamic pressure at the disk interface [33]. Therefore, the *MRR* may not always increase linearly with the speed.

The mechanical models are not sufficiently accurate as they ignored the chemical action which is an important part of the process. Luo and Dornfeld [34] give a general model which considers the chemical corrosion:

$$MRR = \rho_w NV_{removed} + C_0 \quad \text{Eq 10}$$

where ρ_w is the density of the abrasive disk, N is the number of the active particles, $V_{removed}$ is the removal rate of a single particle, and C_0 represents the removal rate caused by chemical corrosion. This model considers both the mechanical action and chemical action in random-orbital polishing. However, for a random process, it will not be accurate to use a constant to describe the corrosion, thus this formula will not be used.

The angular velocity (ω) is calculated as 1047.33 rad/rev, where ω is the angular velocity, and r is the radius of the circular path for the motion (abrasive disk diameter divided by 2). Thus, the linear velocity (V) is 66.5 m/s.

Since the approximate force applied is 3.485 kgf by default, force per surface area is 0.0275 kgf/cm² and the corresponding pressure P is 0.0027 MPa for a disk diameter of 127 mm. Therefore, the material removal rate (*MRR*) for random-orbital polishing is calculated as:

$$MRR = kPVt = (1) \times 0.0027 \times 6650 \times 540 = 9695.7 \text{ cm}^3/\text{s} \approx 9.7 \times 10^{-6} \text{ mm}^3/\text{s}$$

Where

$$k = 1$$

$$P = 0.0027 \text{ MPa}$$

$$V = 66.5 \text{ m/s}$$

$$t = 540 \text{ seconds}$$

For the rotary polishing method with a disk diameter of 102 mm and cutting speed at 12,000 rpm, the velocity is 64.1 m/s and the pressure P is 0.00585 MPa due to the increased weight of the tool. The MRR is calculated as $20.2 \times 10^{-6} \text{ mm}^3/\text{s}$, which is approximately doubled in value as compared with random-orbital polishing. This is a clear indication that rotary polishing is likely to over polishing the fan blade, if proper control is not implemented. Furthermore, a higher wear is associated with 50% higher MRR and this would contribute towards an increase in consumable costs.

5.9 Slurry analysis for condition 4

Since the roughness and PSD analyses imply that random-orbital in condition 4 show promising results that was meeting target values similar to the vibratory process, it would be beneficial to analyze the slurry produced in condition 4.

In general, aluminum oxide (Al_2O_3) suspensions have a low pH value of 4, which may be detrimental to aluminum alloy fan blades due to potential corrosive attack. Furthermore, an electrical conductivity above 500 mS/cm may also contribute to corrosion. A typical slurry's conductivity is approximately 300 $\mu\text{S}/\text{cm}$. The conductivity could reach as high as 300-500 mS/cm. Thus, a slurry mixture with higher pH value and low conductivity is preferred.

A sample of approximately 30 ml of slurry was collected in a clean glass beaker as shown and the liquid was measured for pH and conductivity. The pH and conductivity results were measured and recorded to be 7.4 pH and 235.2 $\mu\text{S}/\text{cm}$ respectively which were ideal. The effect of solution pH and conductivity in the properties of the slurry are briefly discussed. The measured results are as follows:

Water (pH) = 7.4

Water conductivity = 28 $\mu\text{S}/\text{cm}$ (maximum)

Slurry (pH) = 7.4

Slurry conductivity = 235.2 $\mu\text{S}/\text{cm}$

As compared with vibratory finishing, the slurry conductivity was measured to be 244 $\mu\text{S}/\text{cm}$ and pH 7.3. The more ions (inorganic dissolved solids) that were present in the water, the higher its conductivity. The conductivity increases with an increase in ionic concentration. The properties of the slurry produced by random-orbital (condition 4) was quite similar to the vibratory slurry in terms of pH and conductivity.

Figure 31 show the morphology of the alumina particles by SEM. The slurry was completely dried at room temperature in fume hood for 1 week. The images under 500 X and 2000 X magnifications were taken under a scanning electron microscope (instrument used was JEOL 7600, 5 kV).

For SEM analyses, it can be concluded that the colloidal silica accumulated into a porous bulk structure, which is attributed to its large surface area. The size of individual aluminum oxide particles cannot be evaluated from these SEM images, since clear SEM images with higher magnification was difficult to obtain even when the particles were pre-coated before observation to minimize the charging effect caused by the non-conductivity of aluminum oxide.

Figure 31. (a) SEM of the slurry (dried) at 500 X magnification and (b) SEM of the slurry (dried) at 2000 X magnification.

6. Conclusion

This research demonstrates and evaluates the feasibility of a newly developed random-orbital prototype tool with in-line air- and water-cooling capability for localized polishing on fan blade leading edges. The modification work for the tooling is low cost, straightforward, simple and does not require much effort to assemble. The post-polished surface texture of the specimens shows the success in removing scallop height features while keeping the edges within dimensional tolerance and producing the required surface finish. Evaluation of the proposed method narrows the feasibility from four conditions to one recommendation: condition 4 (wet, cold air). Condition 4 performs the best in terms of achieving the target roughness and texture close to the final finishing conditions. The recommended method produces no microstructural defects.

Condition 1 (dry) is excluded in the down-selection because of the high abrasive temperatures, generation of dust and formaldehyde, creating a safety hazard to the operator. Furthermore, the surface topography (Ra) is beyond the desired target and there are visible scratch marks on the surface. Condition 3 is unsuitable because of gouging defect and uneven profile in the microstructure. In addition, the surface topography (Ra) and scratches are similar to that of condition 1.

The key findings are:

1. *Surface roughness.* Random-orbital polishing conditions 2 and 4 can produce the desired surface roughness Ra 0.8 to 1.0 μm and maintain the threshold value of $Ra \leq 2 \mu\text{m}$. It is axiomatic that conditions 1 and 3 have lower the peak-to-valley heights (Sz) by approximately 50% as compared with the existing single-axis rotary method. This reduction in height may not be beneficial for coating adhesion in subsequent processing. However, conditions 2 and 4 has a Sz reduction of 7% and 14% respectively as compared with the exiting method.

The transition of positive Ssk values (initial condition) to negative Ssk values for random-orbital polishing show a change from sharp peaks to rounded peaks, which indicate a lower stress concentration on the surface, which is ideal. The Sku value for random-

orbital polishing in condition 4 indicates that the surface texture is close to a normal distribution, however, the *Sku* value for rotary polishing has the opposite effect.

Statistical functions by FFT and PSD provided further information of the randomness or periodicity of the surface textures. PSD magnitude and amplitude results indicate that random-orbital polishing (condition 4) has a close relationship to vibratory finishing, which achieved the ideal target. In this aspect, condition 4 is identified as the prime technique.

2. *Surface defects*. All conditions 1 through 4 have adequate ability to remove scallop height features on the as-machined fan blade specimens. The thicknesses of the leading edges are all measured and found within acceptable limits. Metallographic cross-sectioning proved that there is no surface distortion, strain lines and abrasive particle embedment on the polished specimens. However, metallurgical analysis showed that random-orbital polishing in conditions 2 and 3 can lead to uneven surfaces and gouging respectively. Although condition 1 reached an elevated temperature of 43.8°C after 9 minutes with P320 grit size, no significant surface degradation is observed in the metallurgical analysis, except for the fine scratch marks. Condition 4 also produced a defect-free surface but has a slight advantage over condition 1 because no scratches were detected.

3. *Hardness*. The hardness of the workpiece under conditions 1, 3 and 4 was similar to the initial condition before polishing. However, condition 2 showed a 10% lower hardness value after polishing with deionized water. Thus, condition 2 failed the hardness requirement and regarded as not suitable.

4. *Abrasive life*. The wear condition of the abrasive disk is highest for conditions 2 and 4, and lowest for conditions 1 and 3. The use of deionized water in conditions 2 and 4 is found to be the key contributor to influence the wear behavior. It is concluded that abrasive disk for condition 4 is moistened, whereas the abrasive disk for condition 2 is heavily wetted by the application of deionized water. As a result, conditions 2 and 4 requires 5 times the number of abrasive disks as compared to conditions 1 and 3 for the

polishing work. The lower air temperatures generated by the cold air gun for conditions 3 and 4 is not observed to have any noticeable effect on the abrasives or slurry.

In terms of abrasive disk wear, there is a trade-off between too much or too little wear which could either be beneficial or detrimental in both scenarios. Condition 4 maintained a good balance of wear and performance. To elaborate, condition 4 proved to be more cost effective in a high-volume production scenario due to the lower number of consumables required.

5. Condition 4 is found to be most favorable without any defects or dimensional issues. This also mean that it takes less time and effort to treat the surface in subsequent processing. By replacing the existing rotary method with random-orbital method, the component surface is expected to be more homogenous after the final processing stage. Based on the evaluation from this study, it is recommended to use random-orbital polishing with deionized water and cold air (condition 4) for effective defect removal and acceptable finishing quality. The key process variables are established to keep the abrasive disk cold and moist during polishing operation.

7. Future work

Future work includes developing improvement in the system by force control and monitoring the tool loads under polishing action. Moreover, instead of using actual fan blade component of thin and curved geometry, thicker and flatter specimens could provide a more accurate material removal rate with less variations.

Since the results from surface roughness and PSD show a close correlation between random-orbital polishing and vibratory finishing, further testing should be explored. This could be beneficial in studying random-orbital polishing as a potential alternate method for vibro-polishing. The only difference is that random-orbital polishing could be exploited for localized touch-up.

Test methodologies could be extended to investigate potential peening effects on the part after polishing. Residual stress analysis by x-ray diffraction (XRD) or center-hole drilling (CHD) are more appropriate methods.

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